Signal Processing 96 (2014) 203–211

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

A waveform design method for suppressing range sidelobes in desired intervals

Feng-cong Li, Yi-nan Zhao*, Xiao-lin Qiao

Harbin Institute of Technology, China

ARTICLE INFO

Article history:
Received 21 August 2012
Received in revised form
9 September 2013
Accepted 29 September 2013
Available online 12 October 2013

Keywords:
Waveform design
Unimodular waveform
Range sidelobe masking
Phase retrieve
Phase-only nonlinear programming

ABSTRACT

We propose an approach for designing unimodular waveforms with low correlation sidelobes in one or more lag intervals. The approach includes an iterative spectral approximation algorithm (ISAA) and derivative-based non-linear optimization algorithms. ISAA is based on power spectral density fitting, phase retrieval, and alternating projection. Phase-only versions of the derivative-based optimization algorithms are also derived. These algorithms eliminate the unimodular constraint by expanding the objective function with respect to the phase vector and by replacing the normal line search with the phase-only line search. The effectiveness of the approach is demonstrated by numerical simulations.

1. Introduction

Traditional radar systems with pulse compression capability prefer probe waveforms with good correlation properties because the output from the matched filter can be seen as the convolution of the radar scene and the waveform's aperiodic autocorrelation function plus additive noise [1]. The blurred range profile complicates the detection and recognition of targets [2,3]. This effect is much similar to the one defined by the image blur model in which the autocorrelation function acts as the point spread function [4]. Thus, some researchers incorporated methods similar to the image restoration to reconstruct the radar scene from the blurred range profile [5]. However, unlike optical imaging devices, active radar can control the probe waveform. A previous work [6] reported that the waveform is a degree of freedom (DoF) for adaptive radar. In 1965, Van Trees [7] pointed out that waveform design is the most efficient method of combating reverberation. In the early history of radar development, the probe waveform is impossible to change at run time. Thus, traditional waveform design algorithms attempt to synthesize a single waveform to cope with various situations.

Today, many advanced radar systems can change the probe waveform on-the-fly. Many scholars have shown interest in fully exploiting the potential of radar systems through adaptive transmit technologies to obtain optimum performance [6,8–13]. Typical examples of these technologies include adaptive polarimetry design, waveform selection, and waveform design. In adaptive waveform selection, the radar system can select the most suitable waveform from the waveform library for the current operating environment to maximize the signal-to-interference-plus-noise ratio (SINR), match the response of the target, and minimize the interference to other radio devices [14]. In an adaptive waveform design, the transmit waveforms are custom designed for the current environment [6]. There are also studies on joint transmit–receive design of which the DoF is further increased, and thus several different problems can be solved simultaneously [15,16]. These technologies require the signal processing

* Corresponding author. Mailing address: Wenhua West Road 2#, Mailbox 55, Weihai City 264209, Shandong Province, PR China. Tel.: +86 631 5687101.
E-mail address: hrbzyn@163.com (Y.-n. Zhao).

0165-1684/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sigpro.2013.09.023

system to have sufficient computing power and the transmitter to handle arbitrary transmit sequences. The development of radar hardware will make it feasible in the near future.

Waveforms with good correlation properties can effectively alleviate the range sidelobe masking problem [17]. However, waveforms for modern radars have many constraints, such as constant modulus [18] and suitable spectrum shape [15,19–24]. The former constraint can maximize the transmitter efficiency, whereas the latter constraint can cancel active interference and clutter. Furthermore, these constrains reduce the DoF of the waveform design, thereby limiting the depth of correlation sidelobes. However, radar is usually not an independent component of the entire system, indicating that other sensing systems and environmental databases can provide it with extra information [25,26]. In addition, new radar operation modes, such as the one provided in [27], can be used to establish a secondary database. Therefore, the range intervals in which the weak targets may exist can be estimated using secondary data. Thus, all range sidelobes need not necessarily be suppressed simultaneously [28–30], and the sidelobes in the desired intervals will be much deeper than that in the traditional waveforms. Furthermore, waveforms with low autocorrelation zones are suitable for high-range resolution radars to extract the range profile of a range-distributed target. These facts demonstrate that waveform design algorithms that can suppress correlation sidelobes in specified intervals must be developed in the modern working environment.

In this study, we develop several waveform design algorithms that can yield waveforms with low sidelobes in arbitrary desired range intervals. The iterative spectral approximation algorithm (ISAA) is based on the idea of alternating projection. According to the relation between the power spectral density (PSD) and the autocorrelation, this algorithm yields waveforms with specified autocorrelation magnitude by reducing the errors between the spectra of the designed waveform and the desired one. Derivative-based algorithms are based on the traditional nonlinear programming. Phase-only searching algorithms are also developed to eliminate the unimodular constraint. This paper is organized as follows. The signal model is described and the waveform design problem is formulated in Section 2. The waveform design algorithms are developed in Section 3. Several numerical examples are provided in Section 4 to demonstrate the effectiveness of the algorithms. The implementation and applications of these algorithms are discussed in Section 5.

1.1. Notation

We denote vectors and matrices with boldface lower and upper case letters, respectively. The imaginary unit is denoted by j. The nth element of a vector $\mathbf{x}$ is denoted by $(\mathbf{x})_n$. The transpose operator is denoted by $(\cdot)^T$, whereas the conjugate and conjugate transpose are denoted by $(\cdot)^*$ and $(\cdot)^H$, respectively. $\odot$ denotes the Hadamard elementwise product. $\mathbb{C}^N$ and $\mathbb{R}^N$ represent complex and real N-space, respectively. $\mathbb{Z}$ is the set of all integers. exp denotes matrix exponential defined as

$$\exp(\mathbf{M}) = \sum_{n=0}^{\infty} \mathbf{M}^n/n! \tag{1}$$

where $\mathbf{M}$ is a square matrix. ln represents matrix logarithm. Diag($\mathbf{x}$) is a diagonal matrix formed from the elements of $\mathbf{x}$. Im is the imaginary part of a matrix, and null denotes the null space of a matrix. $|x|$ denotes the modulus of x, and $\|\mathbf{x}\|$ denotes the Euclidean norm of $\mathbf{x}$. The distance between two vectors $\mathbf{x}$ and $\mathbf{y}$ is defined as

$$\text{dist}(\mathbf{x},\mathbf{y}) = \|\mathbf{x}-\mathbf{y}\|. \tag{2}$$

Accordingly, the projection of a vector $\mathbf{x}$ onto a set S is defined as

$$\text{Proj}_S(\mathbf{x}) = \arg\min_{\mathbf{s}\in S} \text{dist}(\mathbf{x},\mathbf{s}). \tag{3}$$

2. Problem formulation

Consider the scenario in which a strong point scatterer whose echo power is $\sigma_t^2(p)$ exists in the pth range cell. The discrete form of the base band transmit waveform with N code elements is expressed as follows:

$$\mathbf{s} = \begin{bmatrix} s_1 & s_2 & \dots & s_N \end{bmatrix}^T. \tag{4}$$

As mentioned in many papers [5,17,18,29], radar systems prefer unimodular probe waveforms. Thus, we force a constant modulus constraint on the amplitude of the radar code, i.e., $|s_n| = 1$ for $n \in \{1\dots N\}$. The received signal is down converted to base band and undergoes a matched filtering operation at the receiver end. Thus, the noise plus range sidelobe interference for the qth range cell can be represented as

$$\sigma_I^2(q) = u(N-1-|q-p|)|\sigma_t(p)a_{q-p}(\mathbf{s})/N|^2 + \sigma_n^2, \tag{5}$$

where

$$u(x) = \begin{cases} 1 & x \ge 0 \\ 0 & x < 0 \end{cases}, \tag{6}$$

σ_n^2 is the power of the thermal noise; $a_{q-p}(\mathbf{s})$ is the $(q-p)$th lag of the transmit waveform's aperiodic autocorrelation, which can be expressed as

$$a_n(\mathbf{s}) = \mathbf{s}^H \mathbf{U}(n)\mathbf{s}. \tag{7}$$

$\mathbf{U}(n) \in \mathbb{R}^{N\times N}$ is a shift matrix defined as

$$\mathbf{U}(n) = \begin{cases} \mathbf{I}_{N\times N} & n = 0 \\ \begin{pmatrix} \mathbf{0} & \mathbf{I}_{(N-n)\times(N-n)} \\ \mathbf{0} & \mathbf{0} \end{pmatrix} & n > 0 \\ \mathbf{U}^T(-n) & n < 0 \end{cases}. \tag{8}$$

$\mathbf{I}_{N\times N}$ represents the $N \times N$ identity matrix, and $\mathbf{0}$ is the all-zero matrix with a appropriate size. This interference model is a simplified version of the one provided in [31]. If a weak target exists in the qth range cell, then SINR can be expressed as

$$\text{SINR} = \frac{\sigma_t^2(q)}{\sigma_I^2(q)} = \frac{\sigma_t^2(q)}{u(N-1-|q-p|)|\sigma_t(q)a_{q-p}(\mathbf{s})/N|^2 + \sigma_n^2} \tag{9}$$